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Case study: Extend tube life in a waste heat boiler

The sulfur recovery unit (SRU) separates sulfur from sulfur compounds. Within the SRU, a waste heat boiler (WHB) produces high-pressure steam, using the heat generated in this process. Since it operates in a high-temperature, high-hydrogen sulfide (H_2S) environment, the WHB tube is often corroded by high-temperature sulfidation (HTS), and damage to the tube and tube joint frequently occurs. To this end, efforts can be made to extend the tube life in various ways.

SK Energy operates six SRUs. The units experienced several tube leaks, which resulted in repairs following an emergency shutdown process. Periodically, WHB tube inspection is performed during turnaround, and plugging and welding repairs are performed based on the inspection results.

This article presents an SK Energy case study of how to calculate the required tube thickness to select the optimal tube plugging thickness during the turnaround period, and how to extend the life of new WHB tubes. Computational fluid dynamics (CFD) analysis results are included for verification.

Issues during WHB turnaround. In the SRU's high-temperature, high-H_2S environment, tubesheets and tubes are protected by ferrule and refractory. However, due to the deterioration of initial construction and the infiltration of hot gas during operation, corrosion frequently occurs at the tube joint and tube end part.

It is difficult to inspect and repair these parts during a turnaround. They are oxidized and corroded in the high-temperature, acidic atmosphere, and several welding repair, plugging and hydraulic tests must be repeated. Sometimes, the entire WHB is replaced with a new one in a short period of time. SK Energy replaces its WHBs every 5 yr–10 yr.

TABLE 1. Specifications for WHB SR-H45XX

Specification	SR-H45XX
Tube specification	63.5OD × 5t, A192
Tubesheet thickness, mm	38
Ferrule type	Hexagon
Acid gas inlet temperature, °C	1,265
Acid gas outlet temperature, °C	315
Mass flux, kg/m²/sec	20.4
Corrosion rate, mm/yr	0.36
Lifetime, yr*	10

* The service life from installation to replacement; the case of plugging the tube during actual use is faster than this time

At an SK Energy WHB, leakage occurred at an inlet tube joint during operation, resulting in thinning of the tube end and the welded portion (FIG. 1). Acid gas infiltrated into the gap between the front ferrules, causing HTS corrosion. After an emergency process shutdown, the thinner tubes and leaked tubes were plugged and replaced.

SK Energy applied two methods to fix the problem. In the first method, the optimal tube thickness was calculated using the American Society of Mechanical Engineers/American Petroleum Institute (ASME/API) fitness-for-service (FFS) method. As shown in TABLE 1, the WHB is operated in a high-temperature, acid gas atmosphere, so it is important to carefully construct ferrules on the tubesheet during initial construction or turnaround.

In addition, welding repair or plugging should be performed during periodic inspection. As previously mentioned, tube joint welding repair can be challenging. Tube plugging is calculated by defining the tube minimum required thickness (MRT), based on the general ASME Division 1 code. The minimum required thickness was calculated with the finite element analysis (FEA) method, assuming partial corrosion of the tube and tube joint, and the optimum plugging quantity was determined.

The second method introduced the applied best practice for tube life extension and the verification result. To extend

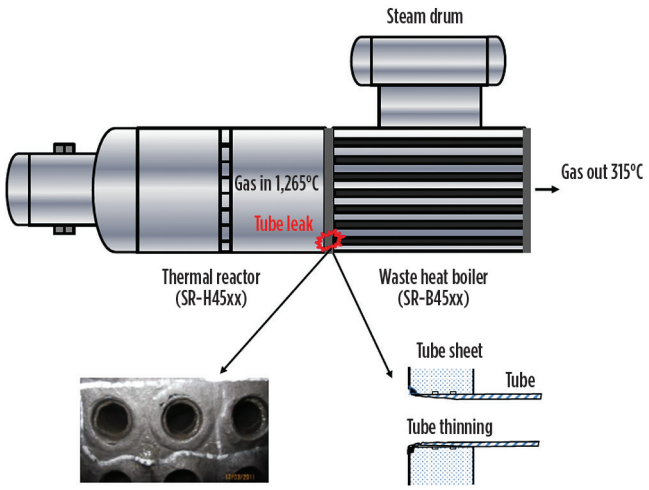
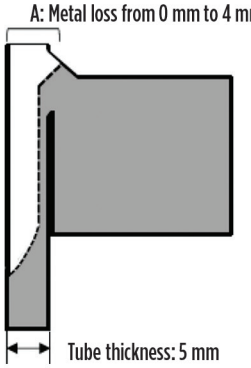


FIG. 1. WHB tube failure showing thinning.



Model	Metal loss (A)
Model 1	0 mm
Model 2	1 mm
Model 3	2 mm
Model 4	3 mm
Model 5	3.5 mm
Model 6	4 mm

FIG. 2. The tube joint weld and the tube inside were simultaneously corroded.

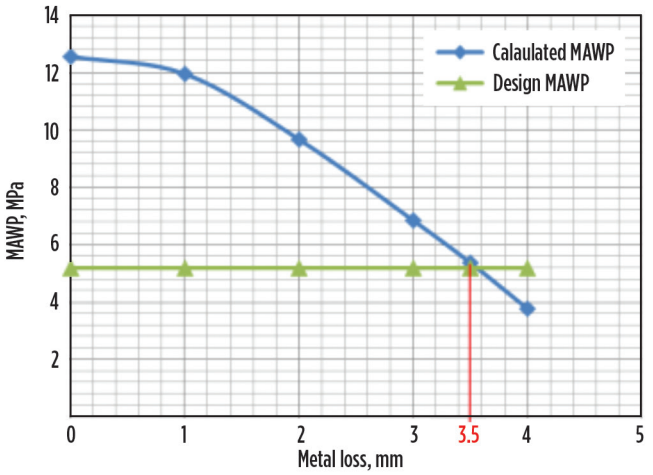


FIG. 3. Calculated MAWP vs. design MAWP for LD2 transient operation (non-axial load).

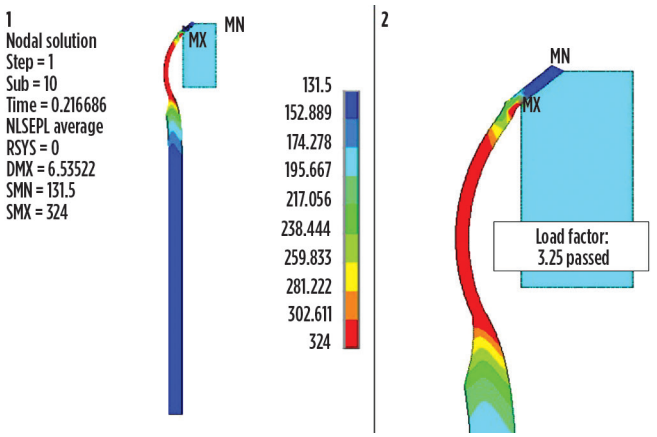


FIG. 4. Global collapse for metal loss of 3.5 mm in LD2 transition operation (non-axial load).

the life of the WHB, SK Energy first examined a number of best practice cases introduced in related conferences and papers, some of which were adopted. One example is the application of a new ferrule type and the application of a metal coating to minimize corrosion of the tubesheet. Within this process, CFD was performed to verify the temperature profile of the tubesheet.

TABLE 2. API 579-1 Load increment factor for each load case

Case	Load condition	Failure type	Required load factor
LD1	Steady-state operation[1]	Global collapse	2.71[3]
LD2	Transient operation[2]	Global collapse	3.15[4]
LD3	Steady-state operation[1]	Local failure	1.53[5]
LD4	Transient operation[2]	Local failure	1.53[5]

Notes
[1] Temperature + pressure load
[2] Pressure load only
[3] $0.86\beta\ (P + P_s + D + T) = 0.86 \times 3.5 \times 0.9 = 2.71$ (API 579-1, Table B1.4)
[4] $\beta \times (P + P_s + D) = 3.5 \times 0.9 = 3.15$ (API 579-1, Table B1.4)
[5] $1.7 \times (P + P_s + D + T) \times RSF_a = 1.7 \times 0.9 = 1.53$ (API 579-1, Table B1.4)
where:
P = Internal and external maximum allowable working pressure
P_s = Static head from liquid or bulk materials
D = Dead weight of the vessel, contents and appurtenances at the location
T = Self-restraining load case

TABLE 3. Analysis results for MRT (non-axial load)

Metal loss, mm	Remaining thickening, mm	Global collapse		Local failure	
		LD1	LD2	LD3	LD4
0	5	Pass	Pass	Pass	Pass
1	4	Pass	Pass	Pass	Pass
2	3	Pass	Pass	Pass	Pass
3	2	Pass	Pass	Pass	Pass
4	1	Pass	**Fail**	Pass	Pass

Method 1: MRT calculation with finite element method.

WHB tube thickness is typically calculated by considering internal and external pressures, according to ASME Section 8, Division 1. In this case, the thickness was calculated over the entire length of the tube. In the case of the WHB, approximately 3.63 mm were required per unit of external pressure.

Application of this criterion required plugging at least 35% of the tube, which could affect the throughput of the process. In fact, no tube leak occurred at much lower residual thicknesses. The presumed reason is that the corrosion did not occur over the entire length of the tube, but was partially corroded to the tube inside the tube joint and the tubesheet.

It was necessary to minimize the tube plugging to avoid affecting the throughput. The API 579 FFS method was applied, using the following specifications:

- **Design:** Tube side—3.5 kg/cm^2 at 353°C; shell side—53 kg/cm^2 at 290°C
- **Tube specification:** 63.5 mm outside diameter × 5 mm thickness (ASME SA192)
- **Tube joint:** Seal welding and heavy expanding with two grooves
- **Corrosion:** 1 mm–4 mm in the length of the tube joint and tubesheet was considered (FIG. 2).

The system generates a system load, which is the axial load of the tube as the temperature rises. The system load should be reflected in the evaluation, but the SK Energy tube joint is made of seal welding and heavy expanding with two

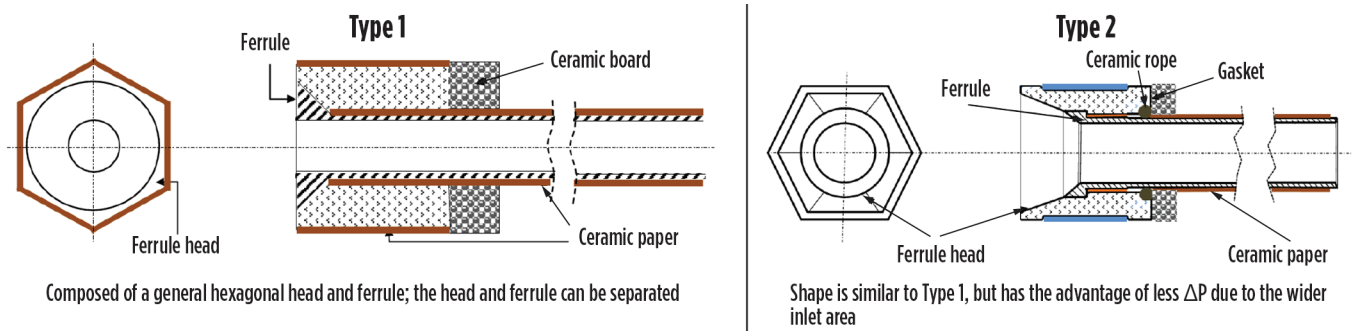

Type 1
Ferrule
Ceramic board
Ferrule head
Ceramic paper
Composed of a general hexagonal head and ferrule; the head and ferrule can be separated
Type 2
Ceramic rope
Gasket
Ferrule
Ferrule head
Ceramic paper
Shape is similar to Type 1, but has the advantage of less ΔP due to the wider inlet area

FIG. 5. Ferrule types.

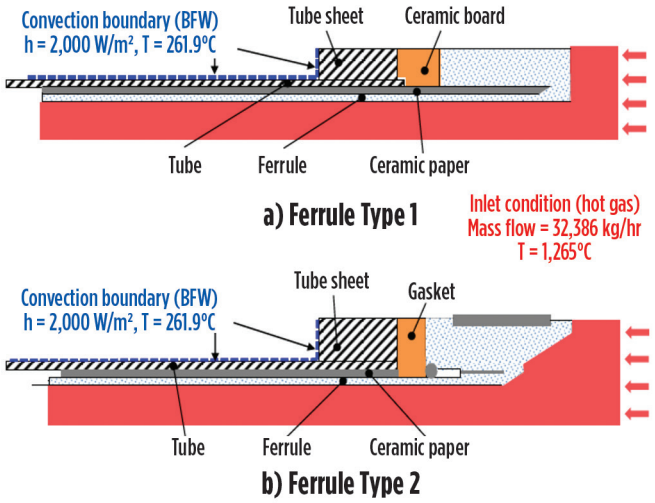


FIG. 6. Boundary conditions for CFD.

grooves. The expanding part supports the thermal axial load, and for this reason the non-axial load condition was adopted for this evaluation.

As shown in FIG. 1, the tube joint welding part and the tube inside in the tubesheet are linked. In SK Energy's experience, the tube joint and tube end were simultaneously corroded, and the tube inside (protected by ferrule) was found to be relatively unaffected. For the conservative evaluation, it was assumed that the tube inside in the tubesheet section was also corroded. As shown in FIG. 2, the corrosion model of 0 mm–4 mm was analyzed.

The evaluation method was conducted according to ASME/API 579 B.1.2.4, "Elastic-plastic stress analysis method." TABLE 2 shows four types of load cases: LD1, LD2, LD3 and LD4. Load conditions were considered in two types of operation: steady-state operation considering temperature and pressure, and transient operation considering pressure only.

As shown in TABLE 3, LD2, a transient condition considering only pressure load, did not satisfy the global collapse condition between a metal loss of 3 mm–4 mm (FIG. 3). In the case of a steady-state operation (LD1), in which temperature and pressure are considered at the same time, the stress is relaxed as the temperature rises. The exact required thickness can be found by increasing the collapse load, as shown in TABLE 4.

In SK Energy's WHB, up to 3.5 mm of metal loss was observed after plugging (FIG. 4). The remaining thickness can be used up to 1.5 mm.

TABLE 4. MRT for LD2 transient operation (non-axial load)

Metal loss, mm	Collapse load, MPa	MAWP, MPa
0	39.54	12.55
1	37.63	11.95
2	30.44	9.66
3	21.55	6.84
3.5	**16.9**	**5.36**
4	11.86	3.76

TABLE 5. Modeling cases

Case	Analysis conditions		
1	Ferrule Type 1	3 mm of tube projection	No gap between ferrules
2		No tube projection	
3		3 mm of tube projection + gap between ferrules	
4	Ferrule Type 2	No tube projection	No gap between ferrules
5		No tube projection + gap between ferrules	

TABLE 6. Highest temperature of tube end

Case	Highest temperature, °C	Condition
1	301.7	Ferrule Type 1
2	298.1	Ferrule Type 1 + no tube projection
3	315.2	3 mm of tube projection + gap between ferrules
4	**322**	**Ferrule Type 2 + no tube projection**

Method 2: Extend WHB life with CFD analysis. As previously mentioned, the most vulnerable parts of the WHB are the inlet tube joint and the adjacent tube inside. Several methods have been applied to minimize HTS in this area:

1. A thermal spray coating is applied to the nickel on the tubesheet and tube inside to improve HTS corrosion resistance
2. Tube-end projection is minimized (5 mm to 0 mm) to reduce the hot pin effect
3. Weld throat thickness of the tube joint is increased because it is corroded to the weld

4. A new ferrule is used to reduce the pressure drop of hot gas during operation
5. The heat mass flux of the tube side is reduced.

SK Energy has implemented Items 1–4 at its WHBs. To lower the heat mass flux for the tube (Item 5), the WHB size should be redesigned; however, this method was considered too difficult to implement.

Of the aforementioned items, SK Energy examined the change of temperature profile, using CFD, for the minimization of tube-end projection (Item 2) and a change in ferrule type (Item 4). At one WHB, a small gap was generated between ferrules, and hot gas directly contacted the tubesheet and tube. Each modeling case is listed in **TABLE 5,** and the two types of ferrules are shown in **FIG. 5.** The boundary conditions for CFD evaluation are shown in **FIG. 6.**

In the same ferrule type, the tube-end projection was compared with the case of 3 mm and 0 mm. The temperatures were found to be 301.7°C and 298.1°C, respectively. The 0-mm projection is advantageous because the temperature is 3.6°C lower. During plant operation, a gap may occur between ferrules. In the same ferrule type, the conditions with a 1.5-mm gap and no gap were analyzed. The resulting tempera-

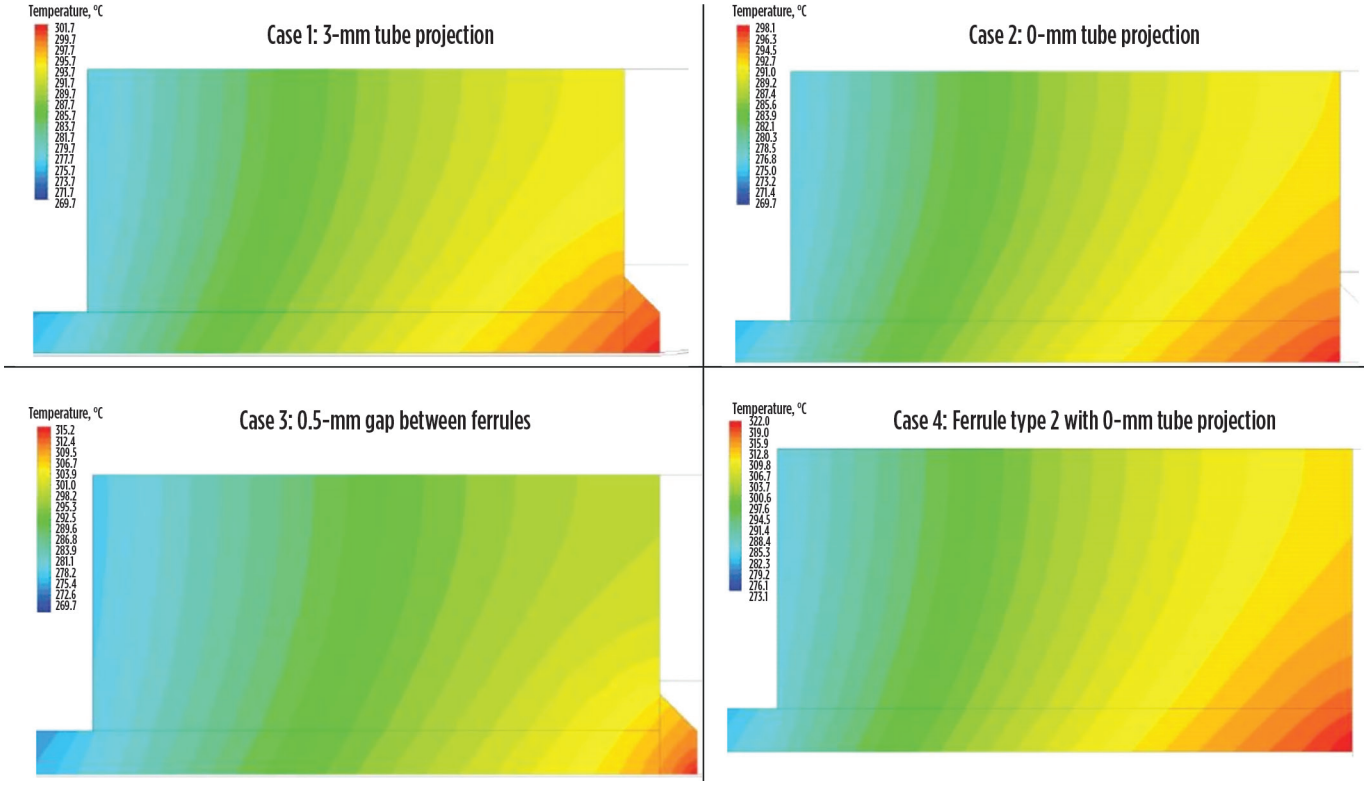

Temperature, °C
Case 1: 3-mm tube projection
Temperature, °C
Case 2: 0-mm tube projection
Temperature, °C
Case 3: 0.5-mm gap between ferrules
Temperature, °C
Case 4: Ferrule type 2 with 0-mm tube projection

FIG. 7. Temperature profiles for tube end and tubesheet.

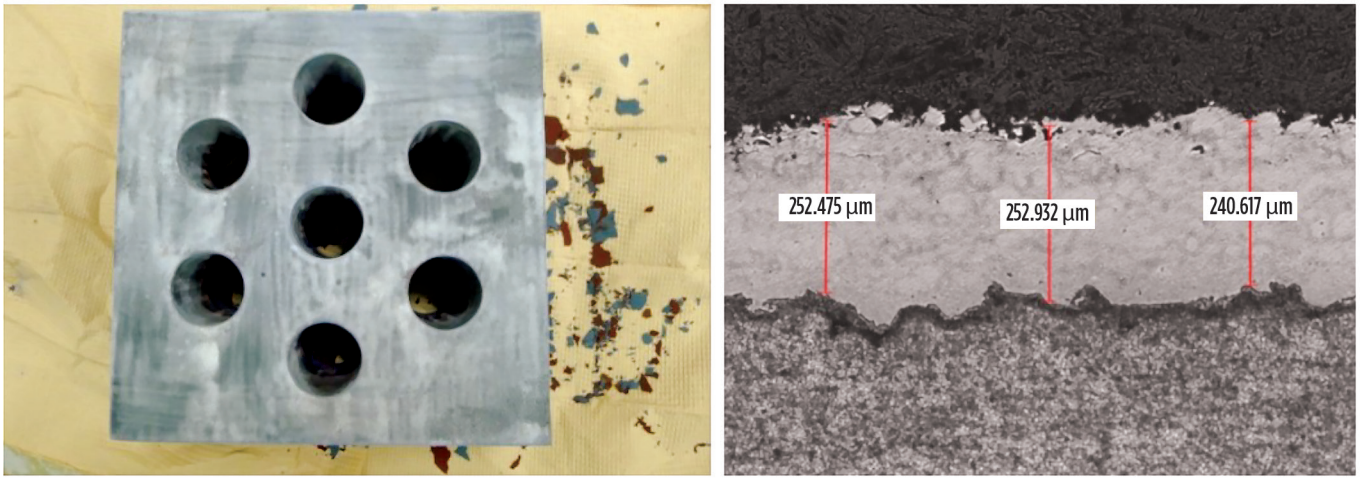


FIG. 8. Specimen for coating test.

tures of 315.2°C and 301.7°C showed a temperature increase of 13.5°C in the presence of a small gap.

As shown in TABLE 6 and FIG. 7, ferrule Type 2 has a higher temperature. This is due to the difference in the thickness of the ceramic board installed under the ferrule. The reason is that Type 1 uses a 25-mm-thick ceramic board and Type 2 uses a 12.7-mm-thick gasket. In the case of ferrule Type 2, the temperature is rather high; however, it is advantageous in the pressure drop side, and the gap can be minimized by applying the packing gasket between hex heads. SK Energy selected Type 2, and the thickness of the gasket was doubled to reduce the temperature.

FIG. 8 shows a thermal spray coating of approximately 200 μm thickness, using nickel alloy material on the tubesheet and tube inside to improve corrosion resistance. To confirm the possibility of disbonding, the test was repeated 15 times after heating to 700°C for 8 hr and then cooling. Disbonding did not occur in the test, and the coating thickness was confirmed to be at least 200 μm.

Takeaway. In WHBs, the tube end and its adjacent welds are exposed to high-temperature acid gas and corrode in a short period of time, unless adequately protected by ferrules. This causes leakage during operation and affects the throughput of the main process at the front end.

Like most oil companies, SK Energy regularly inspects its WHBs during turnarounds and performs welding repair work or plugging to block the tube, according to tube joint inspection results.

An elastic-plastic analysis, carried out according to the ASME/API FFS method and the ASME 8 code base, can be used when selecting the tube for plugging. SK Energy applied 1.5 mm as the plugging thickness instead of 3.63 mm.

The company has also applied various methods to extend the lifespan of new WHBs. Minimizing the tube-end projection reduced the temperature at the site by 3.6°C. If a gap exists between ferrules, the temperature can rise by approximately 13.5°C, so it is important to check the quality to ensure that no excessive gaps are left when installing ferrules. The ceramic board installed on the tubesheet has a significant impact on the temperature, which should be considered when designing a ferrule system.

Finally, when manufacturing a new WHB, the increased thickness of the tube joint welds and the application of a metal coating should be considered for maximum protection. HP

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